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Methodology for Determining Propelling Charge Dimensions for Layered Propellant Charges

by William Oberle

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William Oberle

Weapons and Materials Research Directorate, ARL

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Abstract

The development of advanced gun propellants has led to the use of novel propellant geometries. Of specific interest is the use of layered propellants. This technical note presents a methodology for determining layer thickness and mass to provide optimal velocity.

Acknowledgments

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1. Introduction

The development of new rounds for direct or indirect fire gun applications is an involved process requiring the integration of the launch package and propelling charge to satisfy desired operational constraints. Constraints include gun geometry, such as launch package travel and chamber dimensions; and chamber and gun tube maximum pressures. A first step in this integration process is to determine the propelling charge mass and geometry necessary to achieve the desired launch package velocity. For direct fire applications, the goal is, generally, to achieve maximum possible velocity. Indirect fire applications focus on achieving a specified range of velocities to permit zoning. If the propelling charge consists mainly (>90%) of a single geometry and is chemically homogeneous, the methodology for determining the charge mass and geometry is relatively straightforward as illustrated in the next section. However, advances in propellant formulation and manufacturing have resulted in the recent use of layered propelling charges as shown in Figure 1. These layered propellants consist of an outer layer of propellant that has a slower burning rate than the inner layer propellant material. Thus, the propelling charge is nonhomogeneous in its chemical composition and has essentially two different geometries determined by the thickness of the inner and outer layers. Determining the charge mass and dimensions (i.e., geometry) for this type of propellant is more complicated than for a homogeneous propelling charge that has a single grain geometry.

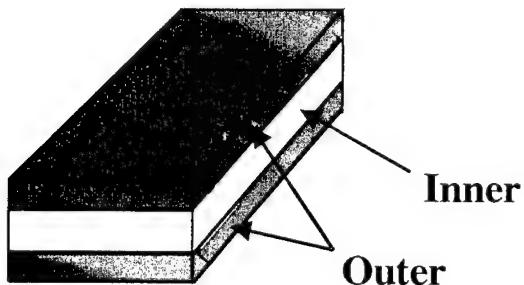


Figure 1. Schematic of layered propellant with slab geometry.

The objective of this work is to describe a methodology for determining the appropriate charge mass for both the inner and outer layers of a layered propelling charge as well as the layer thickness required to achieve prescribed performance levels. This methodology is based upon the use of a 0-dimension (lumped parameter) interior ballistics model. Specifically, the interior ballistics

computer code IBHVG2 [1, 2] is utilized. Although this work will focus on a methodology for achieving optimal performance, i.e., maximum muzzle velocity, the procedure is also applicable to those cases where a suboptimal velocity is desired.

2. Background

For a lumped parameter interior ballistics calculation, the general energy balance equation can be expressed as

$$\begin{aligned} \text{Input Energy} = & \text{ Internal Gas Energy} + \text{Kinetic Energy}_{\text{gas + unburned propellant}} \\ & + \text{Kinetic Energy}_{\text{launch package}} + \text{Losses}. \end{aligned}$$

The input energy is generally the chemical energy released by the burning propellant but it also includes any other input energy source such as the electrical energy associated with electrothermal-chemical (ETC) propulsion. Losses include frictional work, launch package rotational energy, heat convected to the bore, and frictional work. Given the relatively small amount of energy dissipated through losses (<5%), the major components of the right-hand side of the energy equation are internal gas energy, kinetic energy of the gases and unburned propellant, and launch package kinetic energy. Thus, to increase the muzzle velocity, i.e., launch package kinetic energy, the following options are available:

- increase the input energy,
- reduce internal gas energy, and/or
- reduce the kinetic energy of the gases and unburned propellant.

Increasing the input energy implies utilizing a higher specific energy propellant or increasing the propellant mass, or both. For the purposes of propelling charge design, the specific energy of the propellant is a system constraint, i.e., the propellant chemistry is fixed. Thus, increasing input energy can be interpreted as increasing the propelling charge mass,* which is constrained by the available chamber volume. The internal gas energy is a function of the maximum allowable gun pressures and expansion ratio (ratio of chamber volume plus gun tube volume to chamber volume). The larger the expansion ratio the greater the amount of energy that can be extracted from the propelling gases. However, this statement needs to be clarified. It is the volume into which the gases can expand after propellant burnout that really determines the amount of energy that can be

* For most current applications, the amount of electrical energy used in ETC propulsion is less than 1% of the total energy input and is ignored. Electrical energy is best handled by increasing the specific energy of the propellant to include the electrical energy.

extracted. Unfortunately, this means that increasing input energy by adding propellant and extracting that additional energy are inversely related. Since the maximum allowable pressure is fixed, increasing propellant mass implies that the position of the launch package at propellant burnout will be further down the tube. This reduces the volume for gas expansion after burnout and, thus, less energy as a percent of the total energy is extracted from the expanding gases. To say it another way, "The further down the tube the burnout position, the higher the gas pressures (internal gas energy) at muzzle exit." Therefore, the possibility of increasing muzzle velocity by reducing internal gas energy for a given system is not clear. A series of interior ballistics calculations are required to address the trade-off between increasing propellant mass/input energy and the reduced efficiency in extracting that energy. On the other hand, at least a partial answer can be given concerning reducing the gas and unburned propellant kinetic energy. In lumped parameter interior ballistics calculations, the kinetic energy of the gases and unburned propellant is a function of the launch package velocity. For example, using the Lagrange assumptions the kinetic energy of the gases and unburned propellant is given by:

$$\text{Gas Kinetic Energy} = 1/6 m_p v^2,$$

where m_p is the total propelling charge mass and v is the launch package velocity. Since unburned propellant does not contribute to the input energy or to internal gas energy, eliminating unburned propellant will result in increased muzzle velocity. Thus, the propelling charge should be designed in such a manner that no propellant remains unburned when the launch package exits the gun.

Based upon the aforementioned discussion, the basic procedure for determining the propelling charge configuration is:

- (1) select a propelling charge mass,
- (2) adjust grain geometry to meet the maximum pressure constraint(s), and
- (3) repeat steps 1 and 2 for different propelling charge masses until an optimal velocity is determined.

As mentioned in section 1, if the propelling charge has homogeneous chemistry and consists of a single propellant geometry, the determination of the propelling charge mass and dimensions are straightforward using the interior ballistics code IBHVG2. The IBHVG2 code has the capability to perform parametric variations, which can be used to vary the propelling charge mass, and can perform a second variation routine, which can be used to vary the geometry of a single propellant to achieve a specified maximum pressure. The fact that the variation of only a single propellant geometry is allowed is what imposes the restriction of having a single propellant geometry. If there is more than one propellant being used, there may not be a unique geometric solution.

To illustrate both the procedure and the previous discussion, the IBHVG2 code was used to determine the charge mass and geometry to produce maximum velocity for a system with the following parameters:

- bore diameter: 120 mm,
- chamber volume: 10 L,
- launch package mass: 8.95 kg,
- launch package travel: 6 m,
- propellant: 19-Perf JA2, and
- maximum pressure: 700 MPa.

The IBHVG2 input deck is given in Appendix A. Results are given in Figures 2 and 3. Figure 2 shows launch package muzzle velocity and the fraction of the propelling charge burned at launch package muzzle exit as a function of propelling charge mass. As can be seen in the figure, the optimal velocity (1,769 m/s) occurs at a propelling charge mass of 9.6 kg. Even though the propellant is burned out for propelling charge masses up to 10.15 kg, the velocity drops due to the less efficient extraction of energy from the propellant gases (i.e., increasing internal gas energy), as shown in Figure 3.

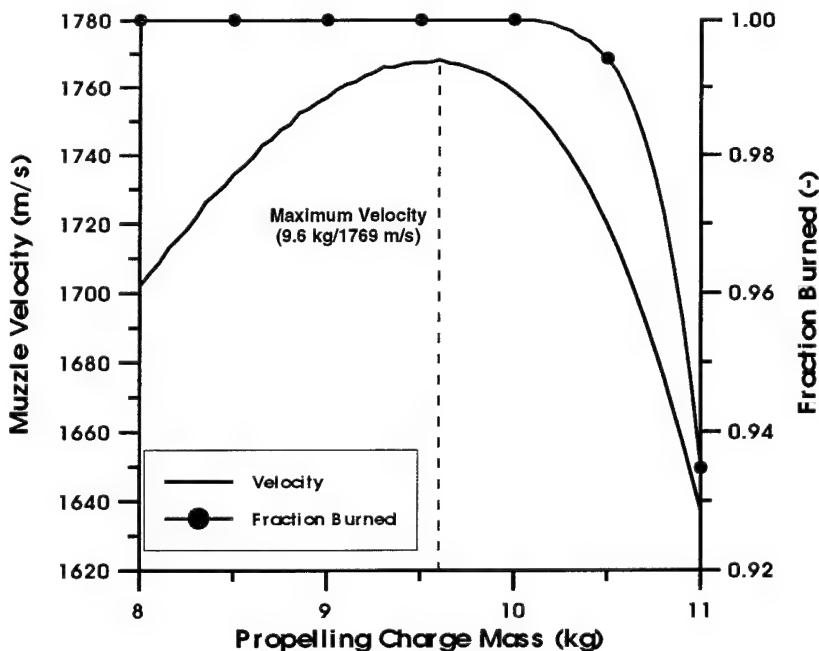


Figure 2. Velocity and fraction burned vs. charge mass.

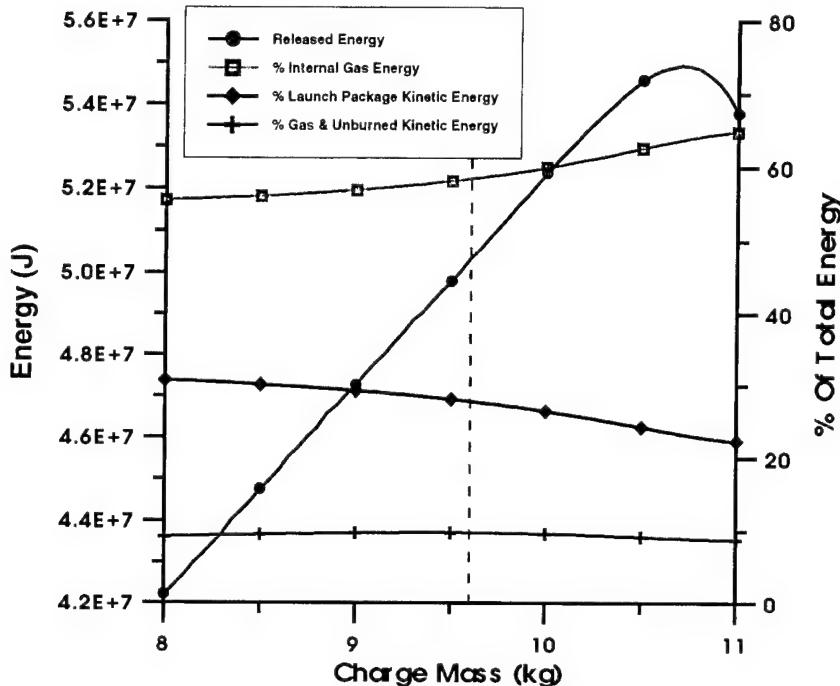


Figure 3. Energy distribution as a function of charge mass.

3. Layered Propellants

If the propelling charge is not homogenous in either chemistry or geometry, then there is not necessarily a unique solution, i.e., unique charge masses and geometric dimensions for the various charge increments, to obtain optimal performance. Fortunately, for layered propellants as depicted in Figure 1, the constraints imposed by the layered nature of the grain geometry does provide for a unique solution if optimal muzzle velocity is desired. The constraints of importance are: (1) the major surface area^{*} of the inner layer is not exposed until the outer layer has been completely burned; (2) the total charge mass must be distributed in such a manner that the number of outer layers is exactly twice the number of inner layers; and (3) for realistic gun systems, optimal performance is achieved by maintaining maximum pressure in the chamber for as long as possible.[†] The last constraint may appear to be contradictory to the example of the last section in which the optimal charge mass was not the maximum charge

^{*} For the majority of layered propellant geometries, the grain thickness is much smaller than the length and width. Thus, only the edge of the inner layer is exposed prior to the burnout of the outer layer.

[†] This assumes burnout of the propellant prior to muzzle exit of the launch package.

mass which had burnout prior to launch package muzzle exit. However, the difference is maintaining maximum pressure and the location of the launch package at propellant burnout. In the example in section 2, even though additional propellant greater than the optimal charge mass could be burned prior to muzzle exit the chamber pressure was not being maintained at or near the maximum pressure. Additionally, in the previous example the location of the launch package at propellant burnout was near the muzzle. In contrast, if the maximum pressure can be maintained in the chamber, then for all existing and proposed propellants in a realistic gun, the location of the launch package at propellant burnout will be significantly short of the muzzle. There is simply not enough energy in the propellant, even at high loading densities, to maintain the maximum pressure for a long period in the ballistic cycle.

To illustrate, consider the limiting case of the constant breech pressure gun [3] applied to the gun parameters from the example in the previous section. For a constant breech pressure gun the propellant is assumed to burn in such a manner that the maximum breech pressure (or any specified breech pressure) is instantaneously achieved and maintained until propellant burnout. Results are shown in Figure 4. The density of the propellant is 1.58 g/cm³, thus, the maximum charge that can be contained in the 10-L chamber is 15.8 kg. As can be observed in the figure for charge masses from 8–15.8 kg the constant pressure calculation results in a continual increase in velocity as the charge mass increases. The location of the launch package at propellant burnout increases up to about 255 cm, which is less than half the total travel of 600 cm.

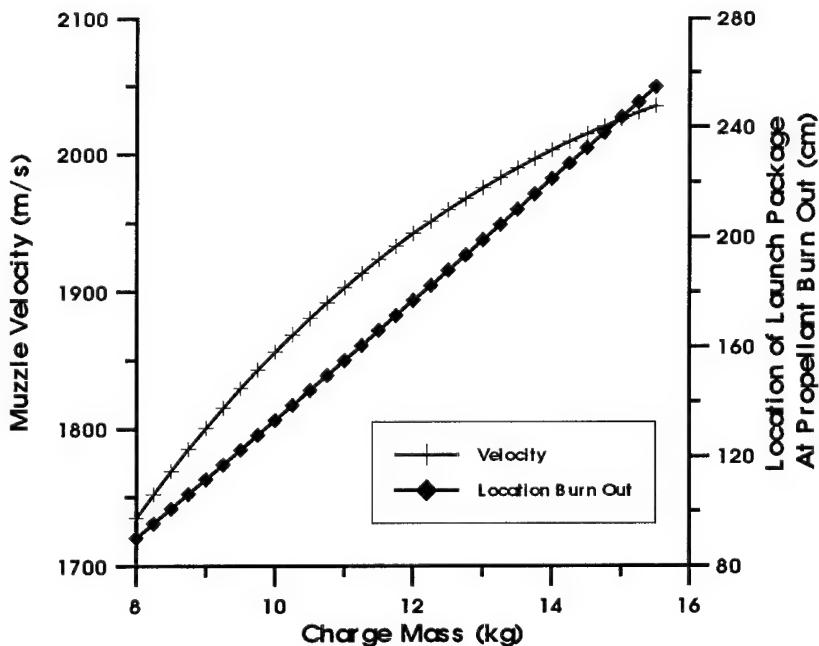


Figure 4. Results of constant breech pressure calculations.

Although achieving a perfect constant breech pressure is extremely difficult, using layered propellants does allow propelling charge configurations that result in breech pressure profiles closer to the constant breech pressure than is possible with chemically homogeneous propellants even if multiple geometries are used. Figure 5 shows the desired breech pressure history and velocity for the 120-mm configuration used in the previous two calculations but with a layered propellant. For the calculation, the burn rate of the inner layer was approximately a factor of 2.5 greater than the outer layer. The outer layer thickness is adjusted so that the second peak in the pressure curve is the maximum pressure. If the outer layer is too thin, then the second peak will exceed the maximum pressure. If too thick, the second peak will be below the maximum pressure and performance will decrease. For layered propellants in which the burn rate ratio of the inner to the outer layer is approximately 2.5, the first pressure peak will occur at about 60% of the outer layer being consumed.

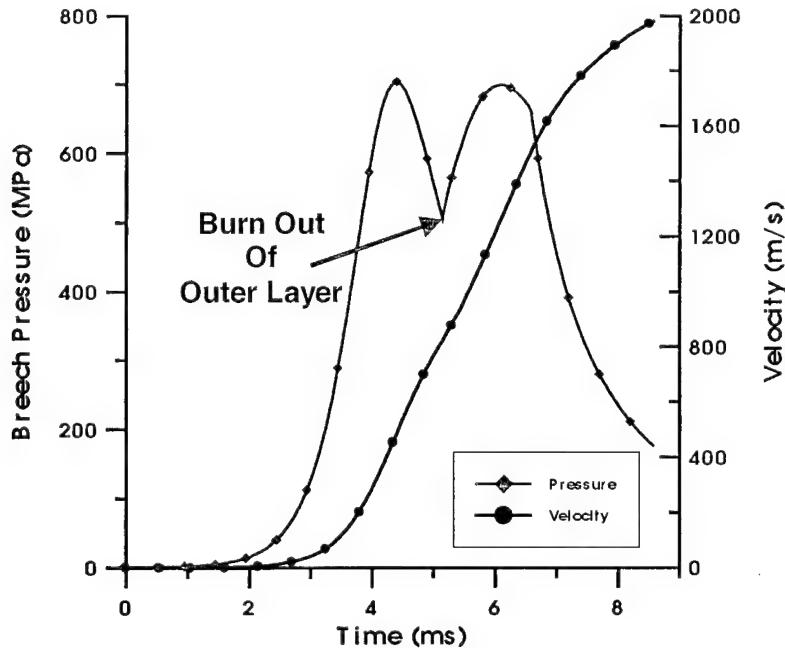


Figure 5. Results for layered propellant (120 mm).

4. Methodology for Determining Optimal Performance Using Layered Propellants

The overall approach is the same as for a homogeneous propellant previously stated: select a propellant charge mass, adjust grain geometry to meet the

pressure constraints, and iterate on charge mass until the optimal velocity is determined. The difficulty is in step 2, adjusting the grain geometry to meet the pressure constraints. The following procedure can be used for layered propellants to achieve the desired pressure history as shown in Figure 5. This procedure assumes that the total propelling charge mass is fixed. Specific implementation details for the procedure will be provided in the next section.

- (1) Determine the number of layered grains required to achieve the first pressure maximum, i.e., first pressure peak is at the maximum allowable chamber pressure.
- (2) Partition the total charge mass between the inner and outer layers.
- (3) Determine the inner and outer layer thickness to produce the number of layered grains determined in step 1.
- (4) Perform the interior ballistics calculation.
- (5) Iterate on steps 2-4 until the second pressure maximum achieves the desired value.

5. Implementation Details

This section assumes that the interior ballistics code IBHVG2 is being used. Unfortunately, most versions of IBHVG2 do not contain a form function that correctly handles layered propellants as defined in this report. IBHVG2 treats layered propellants with layers that are arranged in an “onion skin” geometry. Under this approach, the inner layer edge would not be initially exposed—the entire grain would consist of a shell of outer layer material covering all exposed surfaces. This implementation was motivated by a desire to be able to handle deterred propellants. In the deterrent process all exposed surfaces absorb the deterrent material. One approach that can be used to implement layered propellants in IBHVG2 without modification to the existing code is to treat the inner and outer layers as two separate charge increments. In the code, the thickness of the outer layer is doubled to represent having two outer layers that sandwich the inner layer. Ignition on the lateral surface (lateral and perf surfaces in IBHVG2) of the inner layer is delayed until burnout of the outer layer charge increment. The end surface of the inner layer is assumed to ignite at the same time as the outer layer, i.e., time = 0. It should be noted that this is not an exact representation of the burning of a layered propellant. In actuality, since the inner layer has a higher burn rate than the outer layer, the edge of the inner layer will regress faster than the edges of the outer layer. Thus, a portion of the underside/inside of each outer layer will be exposed as illustrated in Figure 6. Although this will result in an error in the computed burning surface area and thickness of the outer layer, the resulting computed outer layer thickness should

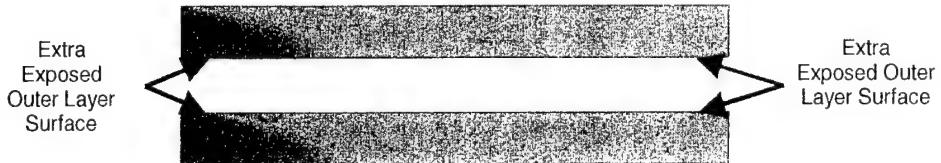


Figure 6. Schematic of additional outer layer surface that is exposed as the grain burns.

be acceptable as a starting point for an actual charge design which is an iterative process involving gun firings and grain dimension adjustment. An IBHVG2 input deck for a layered propellant illustrating the use of separate charge increments is provided in Appendix B.

Step 1: Determine the number of layered grains required to achieve the first pressure maximum.

To determine the required number of grains, start by assigning approximately 30%* of the total charge mass to the outer layer and the remaining amount to the inner layer. Use the \$PMAX option in IBHVG2 and vary the thickness of the outer layer to achieve the desired maximum pressure value. The thickness of the inner layer should be set to a relatively large value. If the thickness of the inner layer is not large enough, the maximum pressure in the \$PMAX search will occur at the second peak. In addition, the maximum value for the first pressure peak must occur before burnout of the outer layer. As mentioned earlier, for layered propellants in which the burn rate ratio of the inner to outer layer is approximately 2.5, the first pressure maximum should occur at about 60% of the outer layer burnt. In fact, the solution will be determined with fewer calculations if the charge masses assigned to the various layers are varied at this step to reach the 60% (or other appropriate percentage) burnt condition.

The required number of layered grains (N) can be determined from the IBHVG2 output in the propellant information section for the outer layer. In the same output section, the thickness for the outer layer should also be recorded for possible use in step 3. This thickness is twice the actual outer layer thickness (T_0).

Step 2: Partition the total charge mass between the inner and outer layers.

On the first iteration, use the mass distribution from step 1. For subsequent iterations, add mass to the outer layer if the calculated second pressure peak from step 4 exceeds the maximum pressure, otherwise reduce the outer layer charge mass.

* The actual percentage of the charge mass to assign to the outer layer will depend on the physical and chemical properties of the layer materials. However, 30% appears to be a reasonable value for most propellant formulations investigated by the author.

Step 3: Determine the inner and outer layer thickness to produce the number of layered grains determined in step 1.

On the first iteration, the outer layer thickness is known from step 1. If the mass distribution is changed in step 2, the required outer layer thickness is given by:

$$T_0 = \frac{m_0}{2NA\rho_0}, \quad (1)$$

where m_0 is the outer layer charge mass, A the lateral surface area of the grain, and ρ_0 the density of the outer layer material. In the IBHVG2 code, the thickness used for the outer layer propellant deck is twice this value. The correct inner layer thickness (T_i) is given by:

$$T_i = 2T_0 \frac{m_i}{m_0} \frac{\rho_0}{\rho_i}, \quad (2)$$

where m_i is the mass of the inner layer and ρ_i is the density of the inner layer material.

Step 4: Perform the interior ballistics calculation.

From the code output, check to make sure that the number of inner and outer layer grains is the same. If the number of grains is not the same, return to step 3.

Step 5: Iterate on steps 2–4 until the second pressure maximum achieves the desired pressure.

A slightly more accurate solution, i.e., inner and outer layer mass and thickness, can be achieved if steps 1 and 2 are reversed and step 5 is changed to iterate on steps 1–4. The number of grains needed to produce the correct first pressure maximum is dependent on the mass of the outer layer. In the procedure previously presented, the number of grains is fixed based upon the total charge mass and not the mass in the outer layer. Although an attempt is made to come close to the correct number of grains by performing step 1 until the maximum pressure occurs at the first pressure peak for approximately 60% of outer layer burnt, the approach presented will end up with the first pressure peak being off by up to 3–4 MPa. However, based upon calculations performed by the author attempting to fine tune the layer masses using the IBHVG2 \$PMAX option (i.e., reversing steps 1 and 2), resulted in a large number of iteration errors in the code. Specifically, the code was often unable to specify the outer layer thickness to the accuracy necessary to achieve convergence on a 600-MHz Pentium III machine. Considering the errors inherent in the approximations of lumped parameter codes, the error in the outer layer surface area discussed earlier and the less than 1 m/s difference in velocity resulting from a 3–4 MPa difference in the first pressure peak, the additional work that results from reversing steps 1 and 2 is not felt to be warranted.

Using the procedure previously described, the result for the 120-mm layered calculation shown in Figure 5 was achieved with four iterations for the fixed total charge mass of the simulation. The IBHVG2 input deck for this calculation is provided in Appendix B. To fully optimize the system the calculation would have to be repeated for other choices for the total charge mass.

6. Summary

In this report, a methodology for determining layer thickness and mass of layered propellants to achieve optimal performance (muzzle velocity) was provided. Additionally, inaccuracies resulting from the manner in which IBHVG2 handles layered propellants and tradeoffs made in the methodology to improve efficiency have been presented. Finally, this procedure has been used by the author and has proven effective in reducing the number of calculations and time required to determine inner and outer layer thickness and mass.

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7. References

1. Anderson, R. D., and K. D. Fickie. "IBHVG2 - A User's Guide." BRL-TR-2829, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1987.
2. Earmhart, J., N. Winsor, and G. P. Wren. "Electrothermal-Chemical (ETC) Extensions to IBHVG2 With a New User's Tutorial." ARL-TR-348, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, January 1994.
3. Oberle, W. "Constant Pressure Interior Ballistics Code CONPRESS: Theory and User's Manual." ARL-TR-199, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, September 1993.

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Appendix A. IBHVG2 Input Deck for Velocity Optimization of a Single Homogeneous Propelling Charge

```
$HEAT
    TSHL = 0.0001143      CSHL = 460.3163186   RSHL = 7861.0916
    TWAL = 293            H0    = 11.348218     HL    = 1
$GUN
    NAME = '120MM GUN TEST CASE'    CHAM = 0.010    GRVE = 0.12
    LAND = 0.12              G/L   = 1.          TRAV = 6.
    TWST = 99
$PROJ
    NAME = 'A'      PRWT = 8.95
$COMM
    'PDIS' VALUES USED WITH PARAMETRIC PRINT OPTION POPT(5)=2
$PDIS
    SHOW='PMAX' DECK='OUT'
$PDIS
    SHOW='CHWT' DECK='PROP'
$PDIS
    SHOW='DIAM' DECK='PROP'
$PDIS
    SHOW='PD' DECK='PROP'
$PDIS
    SHOW='WEB' DECK='PROP'
$PDIS
    SHOW='VMUZ' DECK='OUT'
$PDIS
    SHOW='ZMUZ(1)' DECK='OUT'
$PDIS
    SHOW='LDEN' DECK='OUT'
$RESI
    NPTS = 6           AIR   = 0
    TRAV = 0,.00635,.03048,.046 ,.3226 , 4.747
    PRES = 0.689, 1.58, 8.96, 3.45, 9.6 , 2.84
$INFO
    RUN  = 'Velocity Optimization' DELT = 5E-5  DELP = 5E-5
    GRAD = 2           POPT = 1,1,1,0,2    SOPT = 0
    EPS  = 0.05
$RECO
    NAME = 'NONE'        RECO = 0           RCWT = 0
$PRIM
    NAME = 'BENITE'       CHWT = 0.0155
    GAMA = 1.221          FORC = 548700.
    COV  = 0.0009747145  TEMP = 2041
$PROP
    NAME = 'JA2 19H'      CHWT = 7.971364   GRAN = '19H'
    RHO  = 1580.2         GAMA = 1.2268     FORC = 1150907.
    COV  = 0.0009747145  TEMP = 3436       EROS = 0.0000000
    NTBL = -2 PR4L=68.96,700. CF4L=.00398266,.0019953
    EX4L=.7162,.8796
    LEN  = 0.01905        DIAM = 0.0151384   PD    = 0.000558
    WEB=.0020066
$PARA
    VARY = 'CHWT'  DECK = 'PROP'   FROM = 8
    TO  = 11 BY = .05
$PMAX
    VARY='WEB' NTH=1 TRY1=.002 TRY2 =.0021 PMAX=700.
$END
```

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Appendix B. IBHVG2 Input Deck for Velocity Optimization of a Layered Propellant

```
$COMM

IBHVG2 is not really made to handle layered propellants but deterred
propellants. One way around this is to use two propellant decks.
The first propellant deck represents the outer layer with the
thickness twice the actual outer layer thickness. The second
propellant deck represents the inner layer with burning inhibited on
the perf and end surface.

$HEAT
    TSHL=0.0001143      CSHL=460.3163186     RSHL=7861.0916
    TWAL=293      H0=11.348218     HL=1

$GUN
    NAME='Nominal 120-mm'      CHAM=0.01
    GRVE=0.12      LAND=0.12     G/L=1.
    TRAV = 6.

$PROJ
    NAME = 'Slug'      PRWT = 8.95

$RESI
    NPTS=6      AIR=1
    TRAV=0, .00635, .03048, .046, .3226 , 6.
    PRES = 0.689, 1.58, 8.96, 3.45, 9.6, 2.84

$INFO
    RUN = '105 mm Smart Cargo'      DELT = 5E-5
    DELP=5E-5      GRAD=2      EPS=0.05      POPT=1,1,1,0,2      SOPT=0

$PRIM
    NAME ='BENITE'      CHWT=0.001
    GAMA=1.221      FORC=548700.
    COV=0.0009747145      TEMP=2041

$COMM // Used For determining Pmax Varying the thickness of the outer
layer.
$PMAX
    VARY='THCK'      NTH=1
    TRY1=.0007      TRY2=.0006      PMAX=700.      EPS=1

$PROP
    NAME='Outer Layer'      CHWT=4.165      GRAN='SLAB'
    LEN = .8 WDTH = .05 THCK = .00087812
    RHO = 1646
    GAMA = 1.2771
    FORC = 1075000
    COV = .001237
    TEMP = 2589
    NTBL = 0
    BETA = .00040662
    ALPH = 1.0185

$PROP
    NAME='Inner Layer'      CHWT=9.035      GRAN='SLAB'
    LEN = .8 WDTH = .05 THCK = .00175065
    RHO = 1791
    GAMA = 1.2597
    FORC = 1356000
    COV = .001139
    TEMP = 3713
    BETA = .001392012
    ALPH = .9617
    IGNS = 4,0,4
    THRS = 1,0,1

$END
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